Vertical displacements (uplift) revealed by the PSInSAR technique in the centre of Brussels, Belgium

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Abstract: Radar interferometry (Permanent Scatterers or PS technique) has been applied in and around Brussels. The total area investigated amounts to around 900 km². The ERS data sets covering the time period 1992-2003 have been exploited. Seventy-four scenes of data were used and around 173,000 permanent scatterers (PS) were identified and could be used for time-series analysis. Several ground motion processes have been identified for the first time in the urban environment of the study area. The most spectacular process concerns the uplift located in the centre of Brussels along the Senne river (SW-NE direction).

The area affected by the strongest positive ground deformations corresponds to the zone of water-catchments and pumping from the Cretaceous aquifer since the industrialisation of Brussels (1880-1950). Piezometric levels in northern Brussels (the Vilvoorde area) have increased in the Cretaceous aquifer by 30 m since1992 (50 m since the 1970s when records began). There also appears to be a correlation between the uplifting zone and the former course of the Senne river, and thus with the Quaternary alluvial sediments. It appears that a combined effect of the recharge of the Cretaceous aquifer and the phreatic aquifer of the Senne river explain the observed ground motion.

Many other areas reveal local negative ground motion (settlement), such as those observed at the European Parliament, which seems to record a tilting movement. PS identified on the north side of the building show a downward movement whereas the southern side is rising. Several of the runways at the national Zaventem airport also show subsidence effects. These two examples will be discussed, to demonstrate the high potential of the PSInSAR technique in monitoring urban ground deformations.

Résumé: L'interférométrie radar (technique PSInSAR) a été utilisée au centre et en périphérie de Bruxelles. La surface totale étudiée est d'environ 900 km^2. Les données ERS couvrent une gamme de temps entre 1992 et 2003. Septante quatre images ont été utilisées et environ 173000 récepteurs permanents (RP) ont été retenu et seront utilisés pour réaliser des analyses de séries temporelles. Plusieurs processus de déplacements du sol ont été mis à jour pour la première fois en milieu urbain dans la zone étudiée. Le processus le plus remarquable consiste en un uplift situé au centre de Bruxelles, le long de la Senne (direction SO-NE).

La surface affectée par les plus fortes déformations de sol correspond aux zones de captages et de pompages d'eau dans l'aquifère Crétacé et ce depuis l'industrialisation de Bruxelles (1880-1950). Les niveaux piézométriques situés au Nord de Bruxelles (à Vilvoorde) indiquent une augmentation de 30 mètres du niveau depuis 1992 et de 50m depuis les années septante. Un lien semble exister entre la zone d'uplift et l'ancien tracé de la Senne et donc avec les sédiments quaternaires de la plaine alluviale de cette rivière. Il semble apparaître un effet combiné du remplissage de l'aquifère du Crétacé et de l'aquifère phréatique de la Senne qui expliquerait le mouvement du sol observé.

De nombreuses autres zones locales montrent des mouvements de sol négatifs comme celle au niveau du Parlement européen qui semble subir un basculement. En effet, les RP identifiés sur la partie Nord montrent un mouvement vers le bas à l'opposé de ceux situés sur la partie Sud du bâtiment qui attestent d'un mouvement vers le haut. Plusieurs pistes d'atterrissage de l'aéroport de Zaventem subissent aussi un effet de subsidence. Ces deux exemples seront discutés pour démontrer le potentiel élevé de la technique PSInSAR dans le suivi des mouvements du sol en milieux urbains.

Keywords: remote sensing, hydrogeology, water wells, aquifers, piezometers, deformation.

INTRODUCTION

The Interferometric Synthetic Aperture Radar (InSAR) is a microwave imaging system of the Earth's surface. It has cloud-penetrating capabilities because it uses microwaves. It has day/night operational capabilities because it is an active system. SAR interferometry is a highly effective spatial technique allowing very small surface deformations to be detected and measured from data acquired by the European C-band ERS1/2 and ENVISAT-ASAR satellites. Because of regular acquisitions since 1991, the fifteen years archives of the SAR images have been largely used in order to detect and measure ground movements (with millimetre accuracy), using radar images acquired from an altitude of about 800 kilometres. The InSAR technique is such that deformation rates larger than several centimetres/month for C-band are generally too rapid to be detected. Radar interferometry is very powerful for detecting and quantifying ground deformation over large areas, with accuracy at the millimetre scale. In urban areas, and where outcrops are visible, it is possible to identify numerous back scatterers that do not change their signature with time. These are known as Permanent Scatterers (PS) (Ferretti, Prati & Rocca 2000 & 2001). Therefore, they can be used as ideal objects to estimate progressive ground motion. In urban areas, most of the PS correspond to single buildings whose deformation can be measured every 35 days with an accuracy of better than one millimetre, particularly in the case of slow kinematic change.

PS was developed to detect isolated coherent targets and to tackle the problem of atmospheric delay errors at the expense of many images (over 20) and a sparse, pixel-by-pixel based evaluation. The contribution of topography and atmosphere may be estimated and removed by carefully exploiting their different time-space behaviour. This increases the measurement from centimetre to millimetre accuracy. The combination of all PS resembles a standard geodetic network, although the positions of the points occur randomly and cannot be optimized.

The high repeat rate of new acquisitions leads to a timely identification of changing deformation characteristics. This is important, for example, in monitoring the stability of individual buildings. It is necessary to use long temporal series of SAR data in order to identify coherent radar targets (PS) where motion and atmospheric contributions can be separated, and thus very accurate measurements can be performed.

The Permanent Scatterers Interferometric Synthetic Aperture Radar (PSInSAR) technique is largely used in the framework of the Terrafirma program, one of the ten program dedicated to the Global Monitoring for Environment and Security (GMES) service elements financed by the European Space Agency. The Terrafirma program aims at developing a pan-European ground motion hazard service for the main European cities. The PSInSAR technique applies in various contexts to the detection and assessment of extended ground deformation, having mainly a vertical component (subsidence or uplift). Subsidence hazards involve either the sudden collapse of ground to form a depression or the slow movement or compaction of the sediments near the surface. Numerous phenomena which can cause subsidence have been described in the literature: such as carbonate dissolution that results in caves, sinkholes and karst topography; mining activities that remove minerals from below the surface that can result in collapse phenomena; and fluids (groundwater, oil and gas) that are withdrawn from below the surface for human use can be responsible for subsidence also.

Subsidence caused by compaction as a result of over-pumping of aquifer systems is a problem in urban areas heavily dependent on groundwater resources. Subsidence processes are known and described in the literature in many areas around the world, such as those in the US basins: Las Vegas, Nevada (Amelung *et al* 1999), and Santa Clara Valley, San Francisco Bay, California (Ferretti *et al* 2004). Pumping of groundwater results in surface deformation and raises critical issues from the standpoint both of public protection and economic impact. On the contrary, there are very few publications on uplift phenomenon caused by aquifer recharge.

Cities faced with rising water table are known in several European countries such as Spain (Barcelona) (Vasquez-Sune *et al* 1997), Germany (Dessau) (Riemann 1997), United Kingdom (London) (Simpson *et al* 1989) and Italy (Milan) (Beretta 2003). The main purposes of this paper are to highlight the active uplift process revealed by PSInSAR data in the centre of Brussels, and to discuss the possible causes and consequences of this previously almost unknown process. Secondly; three localities in and around Brussels will be highlighted which demonstrate that other processes are active and require further study to better understand them.

GEOLOGICAL AND HYDROGEOLOGICAL SETTING

Brussels, and more particularly the historical heart of the city, extends across the Senne valley which trends SW-NE. A large alluvial plain, gently inclined towards the north, varies in altitude from 19 m in the south to 13 m in the north.

The hydrogeological structure of the area is formed by several superposed aquifers separated by variable thickness of clays. An alluvial aquifer lies within the Quaternary deposits of the Senne valley. The eastern part of the Brussels Region is characterized by an important aquifer in the sands of the Lede and Bruxelles Formations (Gulinck 1966). The glauconitic sands of the Hannut Formation (Late Paleocene) contain an aquifer separated from the artesian aquifer of the Cretaceous sediments by a clay layer a few metres thick. The Cretaceous is absent in the southern and southwestern parts of Brussels. The thickness of the Cretaceous increases from a few metres to around 20 m towards the north and to more than 40 m in the most eastern parts of Brussels (Buffel & Matthijs 2002). The artesian aquifer of the Cambro-Silurian basement comprises the main aquifer body in the southern part of Brussels. This aquifer is sometimes separated locally from the Cretaceous aquifer if the shales of the basement are sufficiently altered and thick to constitute a barrier. In other places, where no aquitard level is present, we will use the term “Cretaceous-Palaeozoic basement” aquifer.

The Region of Brussels is located above the Brabant Massif basement that covers almost 60% of the Belgian territory. The Brabant Massif comprises a compressional wedge whose core is formed by steeply deformed Cambrian formations (Sintubin & Everaerts 2002) that are flanked to the NE and SW by younger Ordovician and Silurian formations, separated from the core by deep-seated shear zones (Piessens *et al.* 2004). The Brabant Massif was a persistent topographic high with only reduced sedimentation during Late Palaeozoic time. Middle Devonian clastic and Dinantian carbonate sediments form a sedimentary cover with some gaps (Mansy, Everaerts & De Vos 1999 and references therein). The Carboniferous was probably removed by erosion during Jurassic uplift (Vercoutere & Van den Haute 1993). Late Cretaceous chalk deposits (Senonian Age) are preserved. The Brabant Massif experienced an intensive phase of subsidence starting during the late Cretaceous. The deposits of sedimentary Tertiary marine series, composed of clays, silts and sands, occurred during numerous eustatic cycles. For a detailed geological setting of the

Brussels Region, refer to the publication on the urban geology of Brussels, published as part of the IAEG2006 Congress (Devleeschouwer & Pouriel 2006).

DATA OVERVIEW

The ERS1/2 data imaging sets covering the time period 5 July 1992 to 19 November 2003 have been exploited. Seventy-four scenes of data were used covering 11.5 years, but 12 scenes were unusable because of high Doppler Centroid values. The master scene corresponds to the 10 November 1999. The data have been accessed from "dbf" files containing X-Y geographic coordinates in the WGS84 coordinate system. The first step was to convert the WGS84 coordinates in the Belgian coordinate system, called Belgian Lambert 72.

The processed area covers 900 km² from Ternat-Vilvoorde-Zaventem (north side) to Halle-Louvain-la-Neuve (south side). The surface area contains 173,767 PS identified corresponding to a density of 193PS/km². This density is highly variable spatially (Figure 1). Very high PS densities are clearly observed in urban environments like the city of Brussels and also in every village, such as Louvain-la-Neuve where 1080 PS are observed. By comparison, forest areas in southern Brussels, such as the "Forêt de Soignes", agricultural areas and some motorways show a small numbers of available PS.

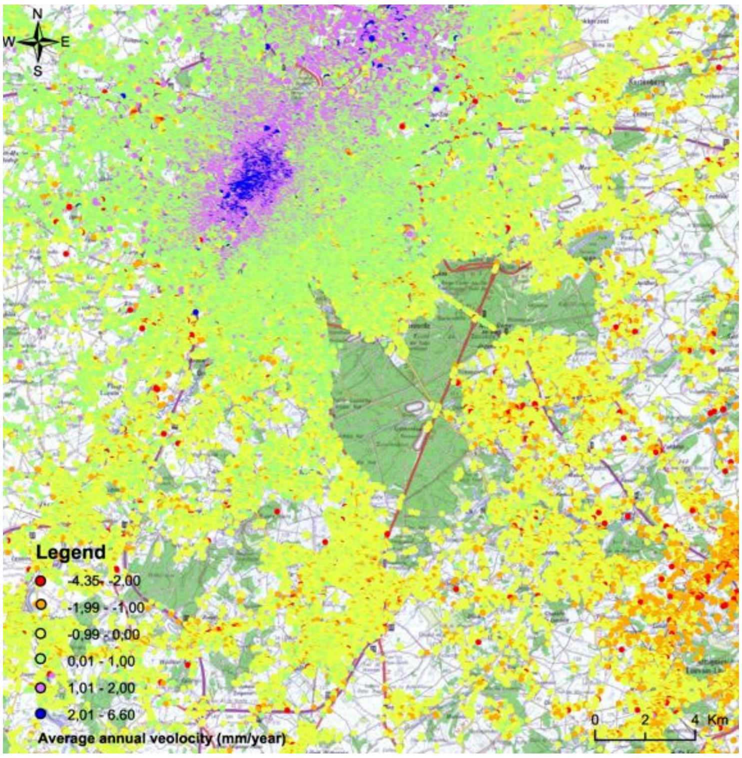

Figure 1. Processed area with the localized 173,767 PS that show the classification based on the average annual velocity (mm/yr). The topographic map (1:100,000 scale) of the National Geographic Institute constitutes the background image.

GROUND MOTION REVEALED AND INTERPRETATION

General overview of the ground motion processes

Inverse Distance Weighted interpolation (IDW) (Lancaster & Salkauskas 1986) assumes explicitly that things that are close to one another are more alike than those that are further apart. To predict a value for any unmeasured location, IDW will use the measured values surrounding the prediction location. Those measured values closest to the prediction location will have more influence on the predicted value than those farther away. Thus, IDW assumes that each measured point has a local influence that diminishes with distance, hence the name 'inverse distance weighted'.

The Inverse Distance Weighted interpolation based on 173,767 PS reveals three main ground motion processes in the study area (Figure 2).

An active uplift phenomenon (blue and purple colours) occurs in the centre of Brussels along the axis of the Senne river (SW-NE trend) in the upper left-hand side of Figure 2. The area around the centre of Brussels is characterized by positive values of ground deformation rate. From the centre of Brussels, the interpolation reveals three elliptical fringes oriented approximately SW-NE, which indicate a decrease in the positive ground deformation values. The highest average annual velocity rate ranges between 3.6 and 2.01 mm/year (blue colour), with the second highest being between 2.00 and 1.01 mm/year (purple colour). This ground motion will be discussed in more detail in the following sections. The interpolation reveals clearly a large area in the middle of the processed zone corresponding to the green and yellow colours, where average annual velocities vary between -1 and +1 mm/year.

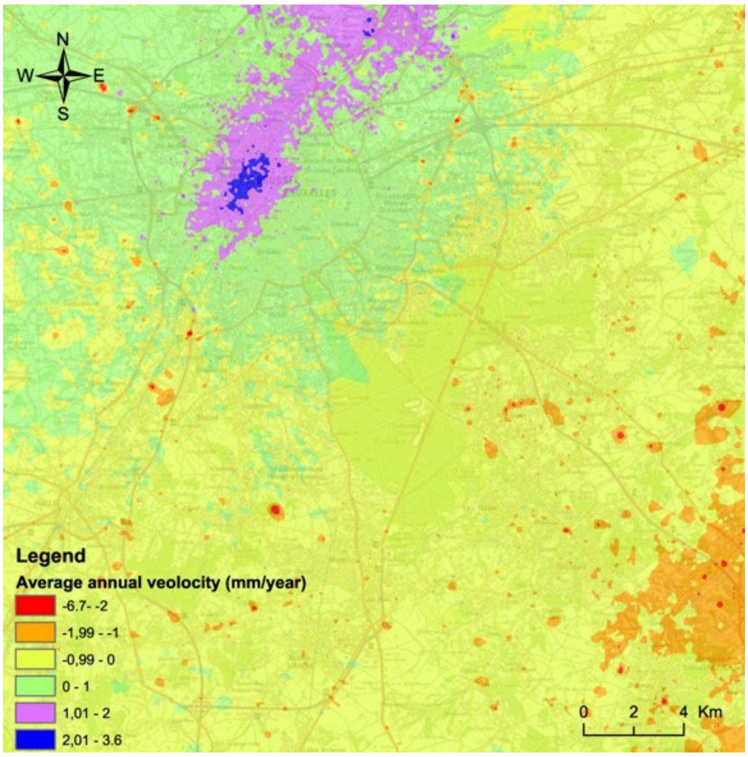

Figure 2. The interpolation (IDW) illustrates and locates the different phenomena that occur in the processed area.

An active subsidence process (orange to red colours) occurs in the area comprising the Ottignies-Wavre conurbation and Louvain-la-Neuve university site, in the lower right-hand side of Figure 2. The subsidence phenomena observed in these areas correspond to detected ground motions. The subsidence process occurs essentially along the Dyle river (approximate SW-NE trend) and covers an area of 33 km². Subsidence has been detected in valleys and on topographic hills. A subsidence gradient is clearly seen in detailed interpolation maps focused on this area and decreases in a SW direction. The highest subsidence values, corresponding to the average annual velocity ranges between -1.6 and - 4.6 mm/year, are observed in the centre of Wavre and along the industrial zone developed along the alluvial plain of the Dyle river. This indicates average ground motion deformations ranging between -1.8 and -5.3 cm over 11.5 years. This is currently under study and details will be published elsewhere. To summarize the current findings, it appears that several geological factors can explain the subsidence. A detailed investigation is required to determine the relative influence of thick peat layers (between 60 cm and 5 m) in the Quaternary alluvial deposits, the variable depth to the top of the Cambrian basement and the presence of an aquifer system in the Cretaceous chalk beneath the city of Wavre and along the valley.

Numerous areas show locally subsidence phenomena on the processed area (orange to red spots). The processes observed in several places indicate local subsidence effect with values ranging between -1.9 and -6 mm/yr. All of them are currently under study and will be detailed, after fieldwork, one by one using all the data available in the archives of the Geological Survey of Belgium (GSB).

Brussels uplift

The ground motion observed in the centre of Brussels (Figure 3), and revealed by the IDW interpolation, corresponds to a large outer elliptical zone (purple colour) characterized by positive ground deformation with average velocities ranging between 1.2 and 2.3 cm over 11.5 years. This area extends to 12 km by 4 km (48 km²). A second inner elliptical, and smaller, area (blue colour) is centred on the historical centre of Brussels and indicates positive ground deformation with average velocities ranging between 2.3 and 5.7 cm over the same period. This covers an area of 4 km².

Water was pumped primarily from the Cretaceous chalk aquifer from the beginning of the industrialisation period of Brussels, in the late ninetieth century, up to the mid-twentieth century. During the initial years, the data in the archives indicate that artesian wells were used for industrial purposes (breweries, dyeing, distillery, refinery, etc). The increasing number of artesian wells, and the increasing water requirements, resulted in pumping from progressively greater depths. The old artesian wells inventoried in our archives have been plotted on the interpolated colour zones indicating the uplift ground deformation in the centre of Brussels (Figure 3). Artesian wells are specifically located along the Senne axis. Most of them (more than 50) are present in the uplifting zones and three of them are found outside this area. Thirteen wells are included in the blue interpolated zones with the highest uplift values. As illustrated by Ferretti *et al* (2004) extensive groundwater pumping led to subsidence and compaction of the basin. Since the 1950s, the industry has progressively disappeared from the centre of Brussels and the wells were progressively abandoned. This situation lead to the reverse phenomenon that corresponds to the recharge of the groundwater aquifer(s). Consequently, groundwater level rises in the local aquifer(s) have produced several centimetres of elastic rebound. If the phenomenon is related to gradual changes of the groundwater regimes, the first step is to check the piezometric level data available to see if the measurements of the piezometric level show some noticeable fluctuations of the aquifers.

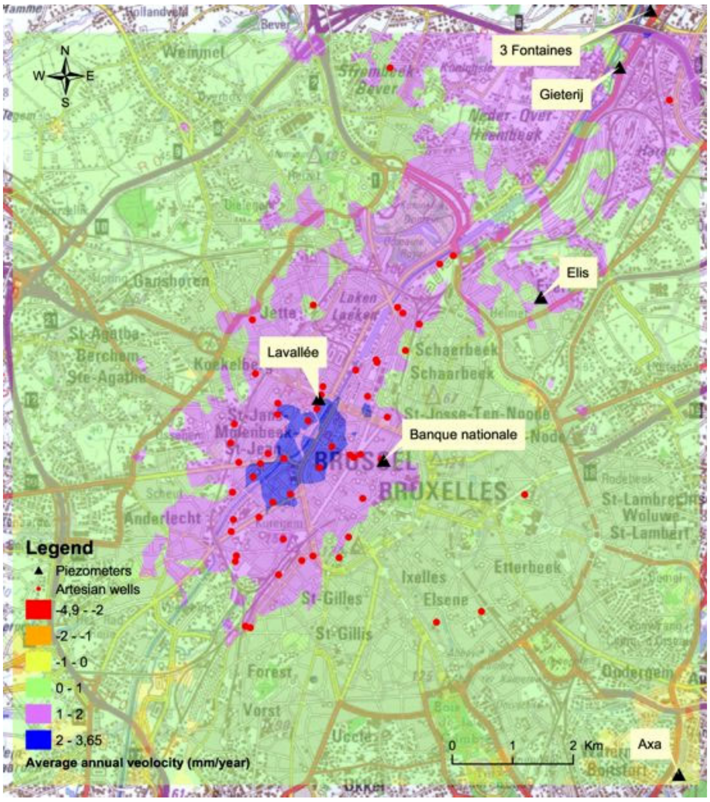

Figure 3. The IDW interpolation is based on the average annual velocity (mm/yr) of the PS in the centre of Brussels. Artesian wells and piezometers are localized on the map. The topographic map (1:100,000 scale) of the National Geographic Institute constitutes the background image.

There are a limited number of available piezometers in this area but they are distributed across the whole area as shown on Figure 3. Two piezometers are located in the Vilvoorde area (north of Brussels), which is situated in the Senne valley. They are included in the outer elliptical zone of uplift. The Flemish groundwater society (named "Vlaams Maatschappij voor Watervoorziening") has provided to us with these data. The others piezometers and available data have been provided by the Hydrogeological Director of the Ministry of the Brussels-Capital Region. One piezometer (Elis) is located in the eastern part of Brussels (the commune of Evere) close to the eastern limits of the outer uplift zone, two of them are present in the centre of Brussels ("Lavallée" in the inner blue interpolated zone and the "Banque Nationale" in the outer purple interpolated zone) and, finally, "Axa" which is relatively far away from the uplifting zone and located on a topographic hill.

Changes in the piezometric level (in metres) against time (in years) for these 6 piezometers are shown in Figure 4. The "Gieterij" piezometer (Figure 4A, Vilvoorde area), in the Cretaceous aquifer, shows a net increase in piezometric level (35 m) before the 1980s, then relative stable conditions during the 1980s followed by a 30 m increase starting in the middle of 1992, up to nearly the end of 2001. The second piezometer in the Vilvoorde area, named "3 Fontaines" (Figure 4B), is also in the Cretaceous aquifer and records approximately similar changes, with a 30 m increase between the middle of 1992 and the end of 2000. It must be noted also that an increase of 20 m in the piezometric level has been recorded since the end of the 1970s. These data indicate that the Cretaceous aquifer has experienced a rise in piezometric level of more than 50 m over a 23 year period. This is characterized by a two-step increase: one before the 1980s and the second after. There are no records that cover the beginning of this process, which may have started before the 1970s. The third diagram, showing the "Elis" piezometer (Figure 4C) reveals a 20 m increase in the piezometric level of the "Cretaceous-Paleozoic basement" aquifer between the beginning of 1996 and the middle of 2004. Similarly, the "Banque nationale" piezometer (Figure 4D) indicates a 18 m increase in the piezometric level in the same aquifer during the 10 years 1994 to 2004. All these data are relatively similar in terms of amplitude and duration of the progressive, positive and constant increase of the piezometric level in the Cretaceous aquifer.

The next diagram concerns the "Lavallée" piezometer (Figure 4E) that indicates a 7 m increase in the piezometric level of the Late Paleocene (Hannut Formation) aquifer during the time period 1998-2004. This information is quite important since it shows that another aquifer records a similar trend, albeit with smaller amplitude compared to the Cretaceous aquifer.

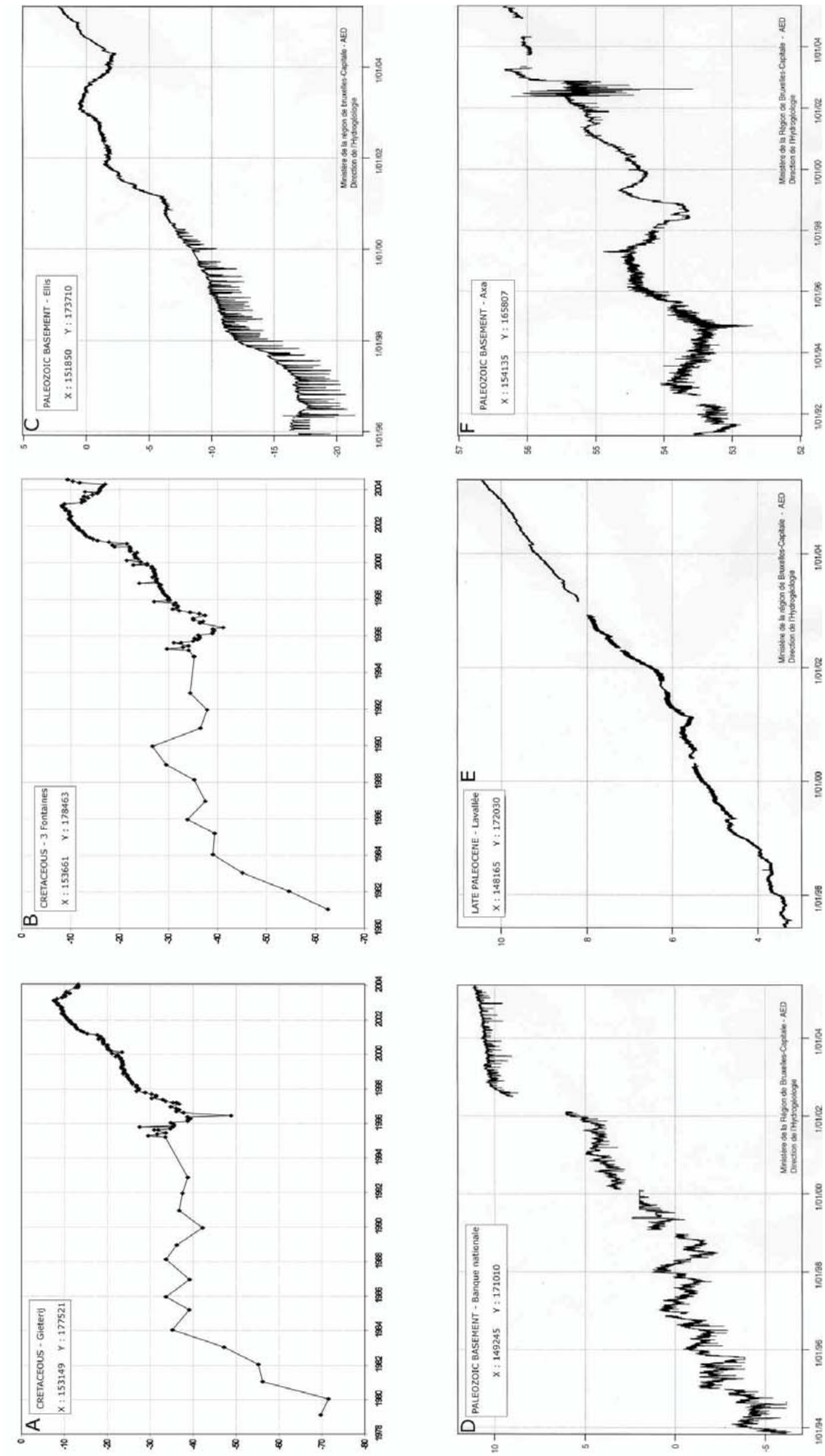

Figure 4. Piezometric diagrams (A-F). The X and Y-axis correspond respectively to the years and elevation in metres.

The sixth diagram corresponds to the "Axa" piezometer (Figure 4F), located in southeast Brussels, and reveals only a 3 m increase in piezometric level during the time period 1992-2004. This indicates also the recharge of the "Cretaceous-Paleozoic basement" aquifer, but to a lesser extent. The water pumping occurring in the valley would have not affected the water-level surface at such a distance within the higher ground.

The vectorization of the old channels of the Senne river in a geographic information system (GIS) has allowed an estimate to be made of the extent of the Quaternary alluvial sediments and thus to the alluvial aquifer of the Senne river. In the valley, the Quaternary deposits have a thickness not exceeding 30 m, so the vertical movements and changes of the level of this aquifer seems to be negligible in terms of amplitude variations and effects on the surface. The only important question that remains unclear is the role played by this aquifer on the peat layers that could have a thickness of a few metres. A detailed study, including mapping, of these peat layers must be undertaken in order to understand what are, if any, the effects on the surface that could be related to the water table drawdown and the shrinkage of the peat under drying conditions.

Similar movements resulting from subsidence-uplift processes following extensive groundwater pumping and recovery of aquifers are described in the literature, as for example the quite rapid uplift of most of the Santa Clara Valley of California. The uplift has been detected by PSInSAR analysis and revealed by 115,847 points using 49 data image acquisitions (Ferretti *et al* 2004). The observed uplift is consistent with previous work showing that recharge and resulting groundwater level rise in the local aquifers of the young sedimentary basin, which contain extensive confined aquifers, resulted in several centimetres of elastic rebound of previously subsiding and compacting basin. Extensive groundwater pumping in the early to mid-twentieth century led to as much as 3 m of land subsidence in the Santa Clara Valley. A combination of reduced reliance on local groundwater, high precipitation in El Niño years and deliberate efforts to recharge the local aquifers contributed to this reversal. An overall pattern of uplift since 1992, with a mean uplift rate of 6.4 ± 2.2 mm/yr, is attributed to an increase in the groundwater levels (Schmidt and Bürgmann 2002).

Local ground movements

As previously mentioned, several places in and around Brussels show localized ground movements. This section presents three case-studies to illustrate the variability in the geological causes of these phenomena and, finally, the last example will show fieldwork analysis on an individual building.

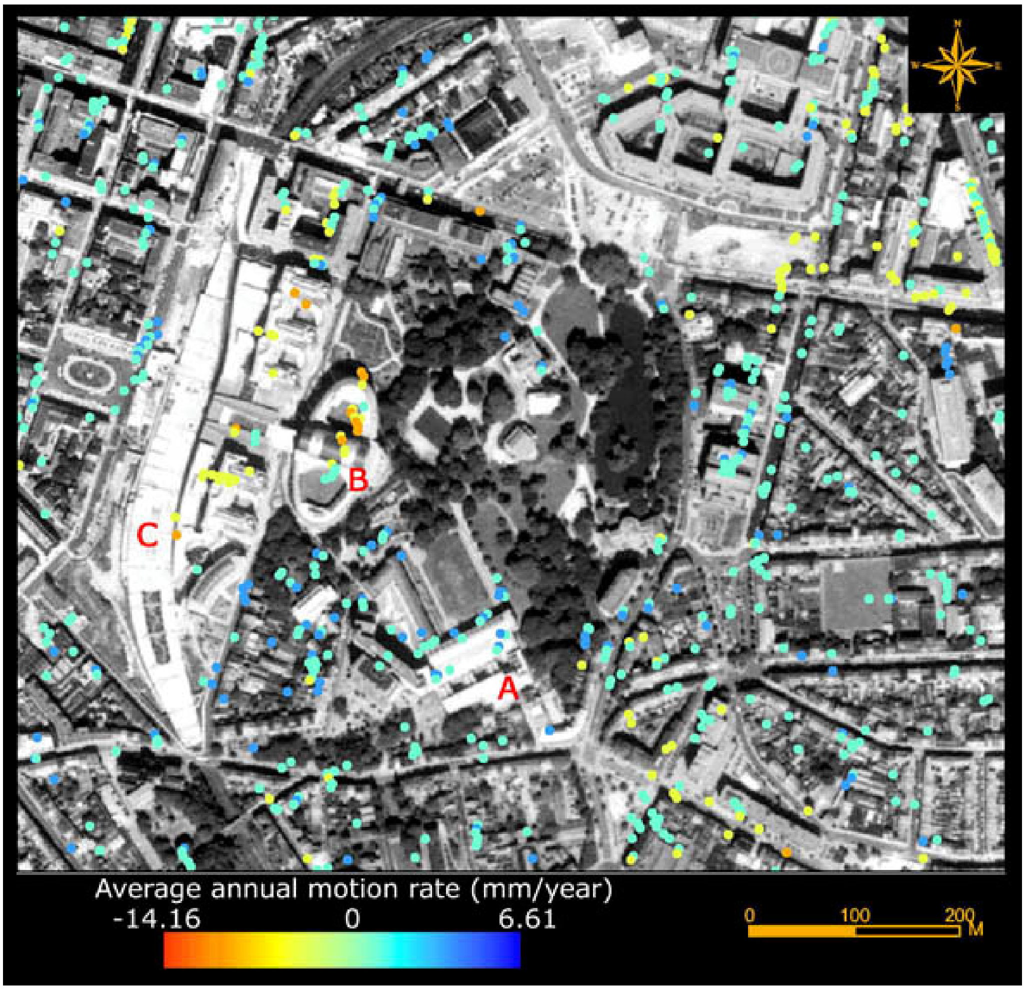

Figure 5. Permanent Scatterers observed near the Geological Survey of Belgium (A), one of the building of the European Parliament (B) and along the railway station of Luxembourg (C). Background images correspond to the Orthophotos of the National Geographic Institute released in 2002.

Firstly, close to the building of the Geological Survey of Belgium (Figure 5, point A) which is stable as indicated by PS values, the European Parliament (EP, Figure 5 - point B) records a differential ground motion event. The southern part of the building reveals positive vertical movements (uplift), whereas the northern part of the building displays negative vertical movements. The average annual velocities of the permanent scatterers indicate a clear gradient from +1.00 (south) to -1.77 mm/yr (north). Field observations reveal inclined trees on slope in the park area located just close to the EP, and a topographic break just in the median part of the building, as the southern part of the EP is on the plateau and the northern part stands on the slope. The building rests on sands of the Bruxelles Formation. The PS results could be explained by a tilting of the EP building caused by slow landslide movements of the sands down the slope in the northern part of the area.

Secondly, the PS points reveal ground motion processes localized on, or close to, the site of the Belgian National Airport of Zaventem (Figure 6). Several phenomena occur in this area: subsidence is clearly detected along the SW-NE and S-N runways, as shown on the background radar image. An active uplift is detected in the buildings of Brucargo (upper left-hand side) and also on the main central building of the Airport (middle of the picture). Many former quarries extracted the sandy calcareous rocks of the Lede Formation or sands in the Bruxelles Formation in this area. An old topographic map dating from 1870 reveals that numerous quarries were widely distributed over what is now the site of the airport. This map has been georeferenced and superposed in the GIS of the PS data. However, the spatial analysis does not show any correlation between these old quarries and the current ground deformation processes. A railway line coming from the south in a tunnel, and an underground railway station, have been constructed underneath the main central airport building and may have contributed to ground surface movements. The exact causes are not fully understood at that present and further work is needed to improve the understanding.

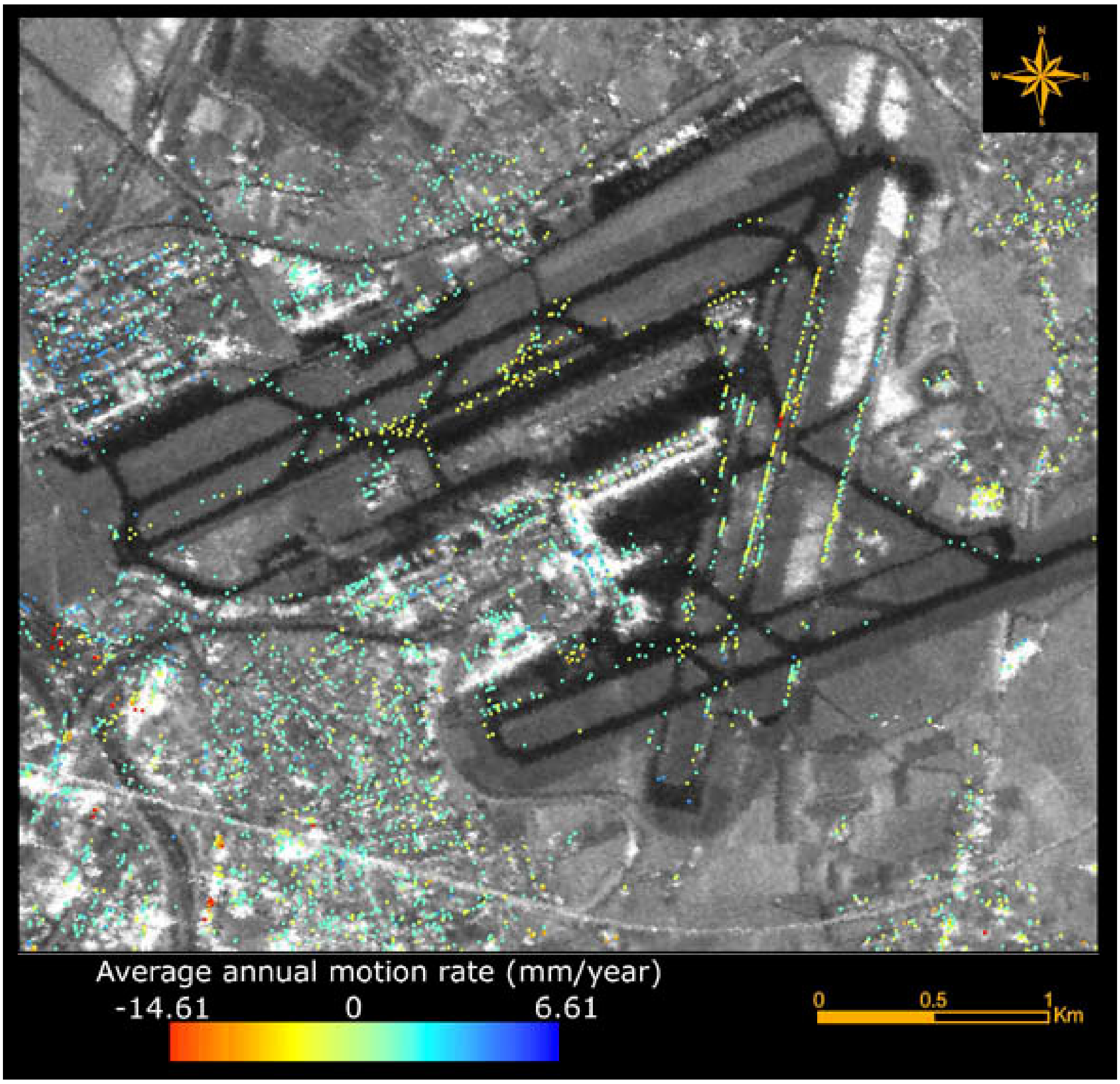

Figure 6. PS points superposed to the radar image centre on the Belgian National Airport.

The last example concerns the application of the PS technique to smaller individual buildings such as the Stock Exchange of Brussels, located in the centre of Brussels where the highest positive ground deformation rate values (uplift) have been detected. Fieldwork reveals numerous cracks on the walls of the buildings. Black lines on the picture in Figure 7 highlight the cracks. It seems that all of them have been filled by cement mortar during a restoration phase of this famous building of Brussels. The most interesting aspect could be the relation between the ground movements (past or present) that occurs in this area of Brussels and the possible damages affecting the urban architecture of this protected monument. The time-series graph of one PS point situated on the roof (GR406) indicates clearly that ground deformation is progressive and has been continuous for 11 years, with more than 3 cm of uplift.

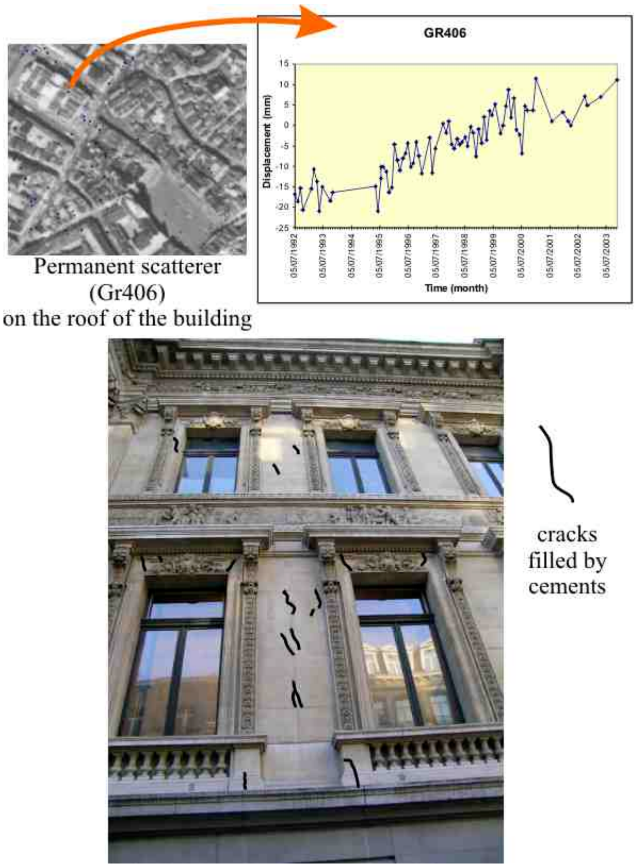

Figure 7. Cracks observed on the walls of the Stock Exchange of Brussels.

CONCLUSIONS

The GSB has implemented the PSInSAR technique in Belgium. It is an innovative method for measuring urban ground motion processes such as subsidence or uplift phenomena. The methodology allows determination, for the first time, of active ground motion processes in a densely populated urban area such as Brussels. With the assistance of GIS tools, the PSInSAR data have been used to demonstrate the usefulness of the combination of radar interferometry with geological and hydrogeological data as an operational methodology to monitor, at the millimetre level, ground uplift resulting from past groundwater pumping activities in Brussels.

The observed process of uplift reported here in Brussels is revealed by Earth Observations systems operative since 1992. The observed uplift indices that recharge of the groundwater aquifers and resulting groundwater level rise in the local aquifers (mostly those of the Hannut Formation, Cretaceous and "Cretaceous-Paleozoic basement") resulted in several centimetres of elastic rebound of previously subsiding and compacting basin. It seems that the alluvial aquifer could only play a negligible impact in the ground deformation observed here. A combination of reduced reliance on local groundwater (replaced almost completely by water transported in excess of 70 km from the Walloon Region), combined with high precipitation has lead to this groundwater recharge of the aquifer(s).

The beginning of this elastic rebound is likely to have started progressively after the end of the extensive groundwater extraction phase, following industrial decline in central of Brussels. There are neither time indices nor available data on the importance of the subsidence process (cone of depression in the piezometric surface) that affected this area during the period of pumping. Several unanswered questions remain for periods when data are available. What are the importance controlling factors (geographic surface, altitude variations, etc) in terms of spatial distribution of the subsidence process? At what period on the time line does uplift take place in the elastic rebound process: at the end? How much uplift (cm or m) will take place before equilibrium is reached? Is building damage confined to the past or is it still taking place? Are there other indices visible today that demonstrate the recharge of the aquifer(s)? These questions remain unanswered and further research is required to better understand the processes operating and the long-term effects of changes to the Brussels region aquifers.

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